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THE ESTIMATION OF YIELD STRENGTH FROM HARDNESS MEASUREMENTS

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Data are presented to show that the yield strength of gun steel and AISI 4340 alloy can be estimated from Rockwell hardness measurements. The expression, $YS = 4.226R_C$, where YS is the 0.1% offset yield strength in ksi and R_C is the Rockwell C hardness of the material, was developed statistically to fit the data. It is shown that the yield strength within a gun tube forging can be estimated from the hardness measurements taken on a small flat area ground on the OD of the gun tube.

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The author would like to acknowledge the assistance of Mr. V. Montuori, Mathematician, who devised the statistical approach and applied it to the interpretation of the experimental data.

INTRODUCTION

Correlations between yield strength and hardness have been developed for many alloy steels in the quenched and tempered condition[1-3]. It has also been shown[4] that the yield strength of a severely cold worked material can be calculated using the expression, YS = H/K, where K is a constant and H is the diamond pyramid hardness assuming that the strain hardening coefficient equals zero. Similarly, it has been shown that YS = H/4 is valid for some low carbon martensites and Fe-Ni alloys[5].

This investigation was made to determine if the 0.1% yield strength within a cannon tube forging can be determined from the R_c hardness measurements on the OD of the tube and to derive an expression which correlates yield strength with hardness for quench and tempered martensitic gun tube materials.

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1. DeFries, R.S., "The Mechanical Properties and Microstructure in 175mm Gun Tube Forgings," Watervliet Arsenal Technical Memorandum, Oct 197?.

2. Bain, E.C. and Paxton, H.W., "Alloying Elements in Steel," 2nd Ed., p. 225, ASM, 1966.

3. Lubahn, J.D., and Chu, H.P., "Optimum Carbon Content for Tempered Martensitic Steels," Journal of Basic Engineering, ASME Trans. Series D, Vol. 90, March 1968.

4. Tabor, D., "The Hardness of Metals," p. 102, Clarendon Press, Oxford 1951

5. Speich, G.R. and Warlimont, H.J., Iron and Steel Inst. 1968 Vol. 206, pp. 385-392.

With these correlations, it would be possible to nondestructively measure the yield strength within large gun tube forgings.

PROCEDURE

Data were developed from a variety of material as shown below:

1. Six large (175mm M113) tube forgings, from several vendors, as received (SN3276-01, 3276-02, 4541-3, 1368, 1139C and 349A).

2. Three additional 175mm M113 forgings, sectioned and re-heat treated to insure a predominantly martensitic microstructure (SN113, 967 and 1144).

3. One autofrettaged 105mm M137 tube (SN 64261).

4. Alloy steel (4337 Mod., 4340 and 4140) heat treated in small sections to insure through quenching.

5. Published data on 4340 and 4140 steel.

The nominal chemical composition of the gun steel alloy and the other materials from which hardness and yield strength data were obtained is shown in Table 1. Discs were machined from six or more locations along the length of the tubes. Tensile mechanical properties were measured through the wall in each of the discs. Also, a one inch wide flat spot was ground on the OD of each of the sections and Rockwell hardness measurements were made. The location of the tensile specimens and the flat spot ground on the OD of the tube sections are shown in Figure 1.

RESULTS AND DISCUSSION

The yield strength (YS)* and the Rockwell C hardness (R_C)

*In all cases, 0.1% offset, unless otherwise indicated.

for the tubes are given in Tables 2 - 6 for the large gun steel alloy forgings, for the 105mm tube and for the reheat treated 4337 Mod., 4340 and 4140 alloys, respectively. Table 6 which shows the YS vs. R_c data as determined from the work of Lubahn[3] and an American Society for Metals Data Table published in a Metals Progress reference publication, is presented for comparison.

A regression analysis to determine an empirical relationship between yield strength (YS) and Rockwell C hardness (R_c) was performed using the model $YS = KR_c$, where K represents the slope of a line passing through the origin (0,0). The results of this analysis for the large gun steel alloy forgings, for the 105mm tube and for the reheat treated 4337 Mod., 4340 and 4140 alloys, are summarized in Figure 2 where all the data are combined, the relation, $YS = 4.226\ R_c$ fits the data. In all cases, except one (Tube #3276-02), the "fitted" line is very good based on the coefficient of determination, R^2 of .9467.

The coefficient of determination $R^2 = \dfrac{\sum_{i=1}^{n} (\hat{Y}_i - \bar{Y})^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}$ is defined for the general linear mode, $Y = A + KX$. When using the form $Y = KX$, i.e. adding a zero constraint on the model, the definition no longer holds. It was decided to take the proportion of the total variability unexplained by the fitted regression equation and subtract

3. Lubahn, J.D., and Chu, H.P., "Optimum Carbon Content for Tempered Martensitic Steels," Journal of Basic Engineering, ASME Trans. Series D, Vol. 90, March 1968.

that quantity from 1 and assume that difference to be a measure of explained variation. Thus, $1 - \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y}_i)^2}$ becomes the measure of precision for the fitted line. This is also a standard form for coefficient of determination.

Brinell Hardness (BHN) measurements were also made on Tube 3276-01 to compare with the R_c readings. When the BHN readings were converted to R_c, the hardness was about 2 points higher than the actual readings obtained on the same pieces. It can be seen that the R_c measurements are slightly better than the BHN measurements (4 ksi vs. 7 ksi YS variation) for predicting the yield strength of the quench and tempered gun steel alloy.

The R_c readings obtained on Tubes 113 and 967 were converted to Diamond Pyramid Hardness (DPH) numbers to determine the K value for comparison or substantiation of the K values previously cited in the literature[4,5,6]. The average K value obtained on these tubes of 2.345 was lower than the values of 3 and 4 previously reported. This difference could be caused by converting the R_c numbers to the DPH numbers, and/or a difference in alloy composition.

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4. Tabor, D., "The Hardness of Metals," p. 102, Clarendon Press, Oxford, 1951.

5. Speich, G.R. and Warlimont, H.J., Iron and Steel Inst., 1968, Vol. 206, pp. 385-392.

6. Cahoon, J.R., Broughton, W.H., and Kutzak, A.R., "The Determination of the Yield Strength from Hardness Measurements," Met Trans., Vol. 2, July 1971.

The 4340, 4337 Mod. and 4140 data, Table 5, also showed that the average K value for these alloys is about the same value as calculated for the gun steel alloy. Therefore, the expression shown earlier could also be used to estimate the YS for 4337 Mod., 4340 and 4140.

The average K value of 4.226 was also calculated from the YS and R_c figures from Lubahn's data[3] and an ASM Data Table, Table 6, which applies only to fully quenched and tempered steels containing more than .30 percent carbon.

CONCLUSIONS

Despite the heavy wall of cannon tube forgings, hardness measurements can be utilized to determine the yield strength (ksi) of large gun tube forgings of quench and tempered gun steel.

The yield strength can be determined from the relationship $YS = 4.226\ R_c$ in the 130 to 190 ksi YS range considered in this investigation. This relationship was statistically determined.

The YS vs. R_c data on large tube forgings was in close agreement with that presented by Lubahn and ASM.

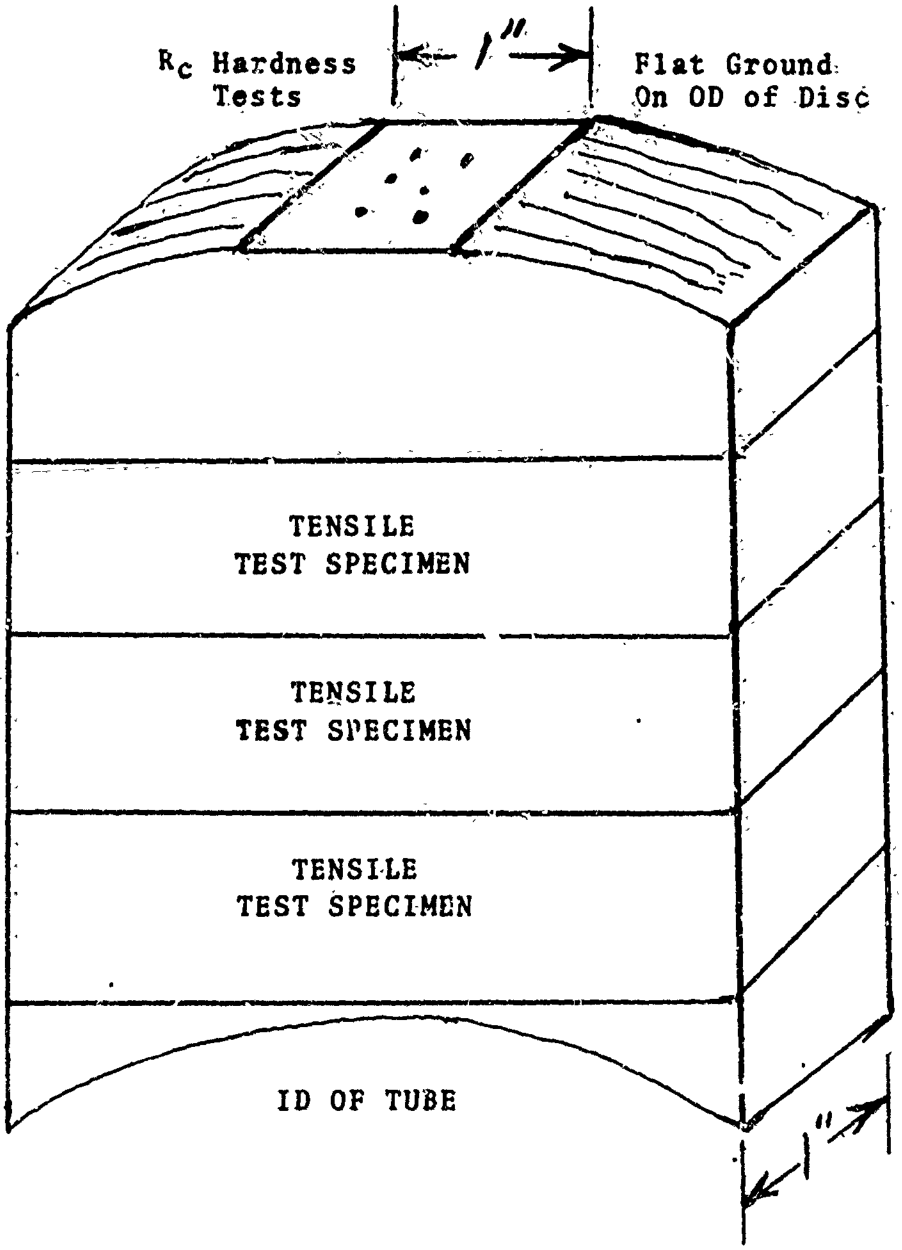

Figure 1. Location of hardness tests and tensile test specimens in the disc sections.

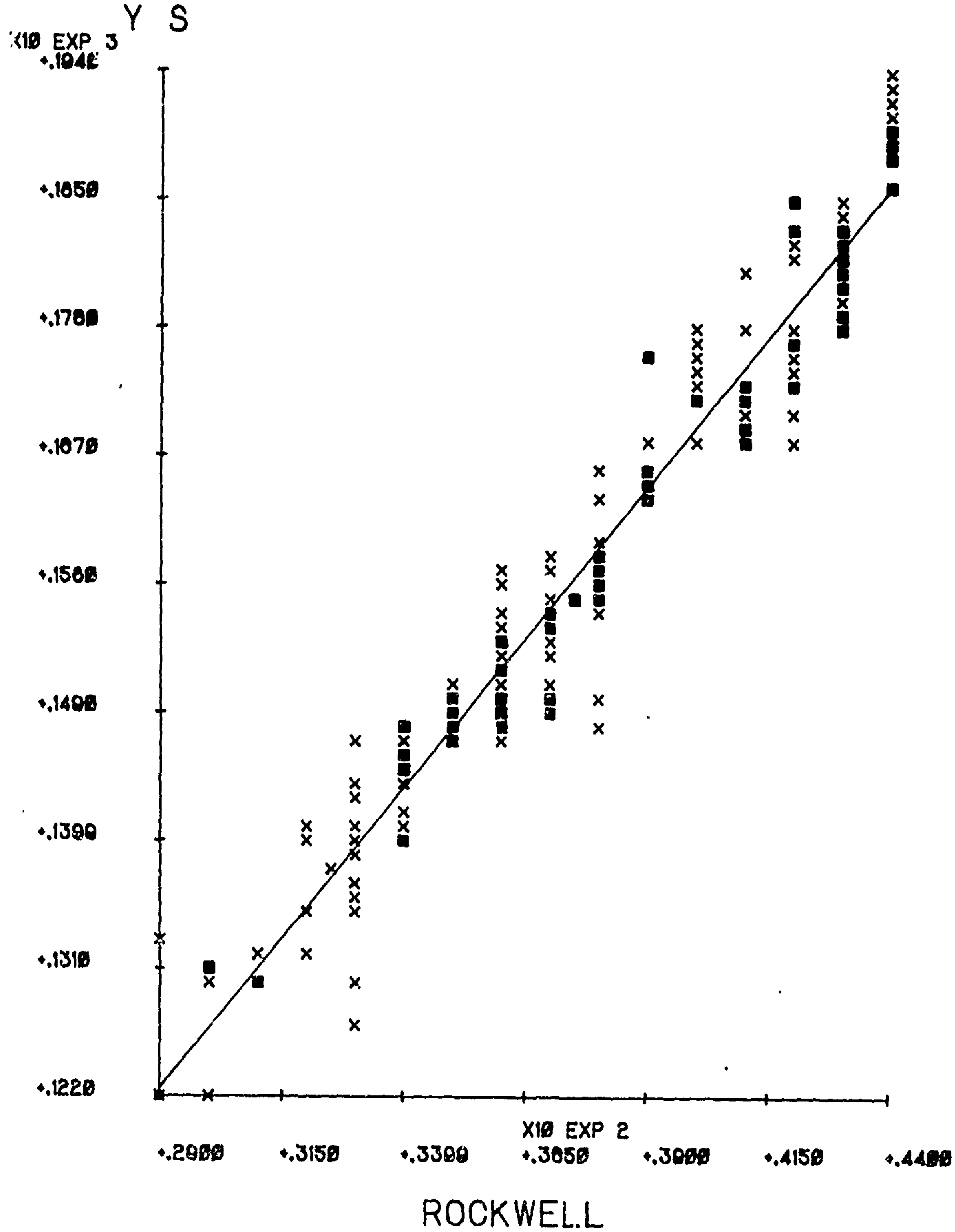

Figure 2. Yield strength vs hardness (R_c)

TABLE 1. CHEMICAL COMPOSITIONS

(Nominal)

TYPE	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu
Gunsteel	.36	.50	.01	.01	.35	3.0	.90	.50	.10	-
4337 Mod	.37	.72	.01	.01	.30	1.8	.77	.35	-	.10
4340	.40	.70	.03	.03	.30	1.8	.80	.25	-	-
4140	.40	.85	.03	.03	.30	-	.95	.20	-	-

TABLE 2. YIELD STRENGTH HARDNESS* DATA

175MM M113 TUBES

TUBE NO. 3276-01		TUBE NO. 3276-02		TUBE NO. 1368	
YS	R_c	YS	R_c	YS	R_c
148 ksi	35	149 ksi	36	176 ksi	41
157	38	149	36	174	39
146	34	149	37	171	40
150	35	148	35	175	40
154	36	150	37	174	40
154	36	150	37	181	42
147	34	151	36	183	42
147	35	150	36	182	42
157	37	160	38	180	41
157	37	161	38	185	42
154	36	160	38	183	42
148	34	160	37	185	43
157	37	159	38	185	42
148	34	158	36	174	39
148	34	159	36	173	40
		159	37	176	40
		149	37	171	40
		151	37	168	39
		150	38	172	40
		148	35	171	40
		150	35	166	38
		149	35	164	38
		148	38	165	39
		150	37	166	39

*Average of six readings

TABLE 2. YIELD STRENGTH - HARDNESS* DATA (cont)
175MM M113 TUBES

TUBE NO. 1139C		TUBE NO. 349A		TUBE NO. 4541-3	
YS	Rc	YS	Rc	YS	Rc
142 ksi	34	145 ksi	34	141 ksi	32
140	34	143	33	140	32
130	33	141	33	132	32
127	33	137	33	135	33
130	30	144	33	130	31
130	31	147	33	139	33
131	30	122	29		
131	30	133	29		
131	30	122	30		
132	31	130	31		
151	35	136	33		
152	36	140	34		
152	36	141	34		
155	37				
156	37				
158	38				
156	36				
157	37				
147	36				
148	36				
148	36				
145	34				
145	34				
147	35				
147	35				
146	34				
148	34				
149	35				
153	36				

*Average of six readings.

TABLE 3. YIELD STRENGTH - HARDNESS DATA
REHEAT TREATED
175MM M113 TUBES

TUBE NO. 1144

YS	Rc
194 ksi	44
190	44
191	44
190	44
190	44
188	44
190	44
188	44
189	44
193	44
190	44
189	44
188	44
186	44
186	44
189	44
184	43
183	43
183	43
183	43
182	43
181	43
181	43
180	43
177	43
178	43

TUBE NO. 1144

YS	Rc
177 ksi	43
176	43
179	43
176	43
168	42
170	42
175	42
174	42
181	43
179	43
172	42
176	42
168	41
169	41
169	41
168	41
171	41
172	41
164	39
165	39
158	38
156	38
153	37
156	37
150	36
150	36

TUBE NO. 113 and 967

YS	Rc
130 ksi	31
135	32
138	32
140	33
144	34
147	35
150	36
154	37
157	38
164	39
166	39
168	40
170	41
171	41
173	42
172	42
175	42
176	43
180	43
182	43
190	44
192	44

TABLE 4. YIELD STRENGTH - HARDNESS DATA

105MM M137 TUBE

TUBE NO.
64261

YS	Rc
188 ksi	42
187	42
186	43
188	42
189	42
187	41
187	42
188	42

TABLE 5. YIELD STRENGTH - HARDNESS DATA

LOW ALLOY STEEL

4340		4337 Mod		4140	
YS	Rc	YS	Rc	YS	Rc
117 ksi	28	175 ksi	40	96 ksi	22
118	28	177	41	114	29
131	31	157	37	127	30
132	31	158	38	129	30
140	33	155	38	132	33
143	33	161	37	133	30
150	36	149	39	134	31
150	36	155	38	146	36
152	36	145	38	168	41
157	37	154	39	189	45
165	39	157	39	206	47
168	39			222	50
174	40			235	53
176	40			246	57
182	45				
191	42				
186	46				
202	47				
210	48				
215	50				
220	52				
227	55				

TABLE 6. YIELD STRENGTH - HARDNESS DATA

LITERATURE

Lubahn Data

YS	Rc
85 ksi	20
90	22
97	24
104	26
111	28
120	30
132	32
139	34
148	36
156	38
166	40
178	42
187	44
200	46
214	48
230	50

ASM Data Table

YS	Rc
69-78 ksi	14
73-84	16
76-90	18
79-93	20
85-99	22
92-107	24
99-114	26
107-122	28
116-131	30
125-141	32
131-146	34
141-157	36
153-170	38
163-179	40
176-185	42